Testing of the International Space Station and X-38 Crew Return Vehicle GPS Receiver

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BIOGRAPHIES

James Simpson has tested navigation sensors for last 5 years with a primary focus on GPS receivers. While at the NASA - Johnson Space Center, Mr. Simpson's work in incorporating a GPS Signal Generator into GN&C Test and Integration Test Facility (GITF) for the International Space Station prepared him for his current subsystem test responsibilities with the Space Integrated GPS/INS (SIGI) at the NASA - Goddard Space Flight Center. Mr. Simpson received a Bachelor of Science in Aerospace Engineering from West Virginia University and is currently pursuing a Master of Science in Aerospace Engineering at University of Maryland - College Park.

Dr. E. Glenn Lightsey is currently an Assistant Professor in the Aerospace Engineering and Engineering Mechanics Department at The University of Texas at Austin. He formerly worked at NASA Goddard Space Flight Center as an Aerospace Engineer during the design and testing of the SIGI receiver. Dr. Lightsey received his BSE degree in Mechanical & Aerospace Engineering at Princeton University, MS in Electrical Engineering at The Johns Hopkins University, and Ph.D. at Stanford University in Aeronautics and Astronautics. He has worked for 13 years in the fields of Guidance and Control and GPS receiver design for space applications.

Dr. Charles Campbell received his Ph.D. from Purdue University in Robotics in 1985. He lead Goddard's Intelligent Robotics Laboratory from 1989 to 1994. Later he designed the safehold and sun acquisition controllers for the Microwave Anisotropy Probe due to launch next year. Most recently he has been working on SIGI. He holds a patent on the "Frequency Scanning Capaciflector" which allows rapid determination of distance to and type of material being scanned from up to 12 inches away.

Dr. Russell Carpenter is an Aerospace Engineer at NASA Goddard Space Flight Center, where he has worked in the Guidance, Navigation, and Control Center since 1998. His current research areas involve formation flying GN&C and GPS development, analysis, simulation, and test. Before coming to NASA Goddard, Dr. Carpenter was at NASA Johnson Space Center from 1987-1998, where his research involved development, analysis, simulation, and test of space flight navigation techniques, future exploration missions, and advanced technology experiments. Dr. Carpenter attended The University of Texas at Austin, receiving his B.S., M.S., and Ph.D. in Aerospace Engineering in 1989, 1991, and 1996, respectively.

Edward Davis is an aerospace engineer with the National Aeronautics and Space Administration at the Goddard Space Flight Center. He participated in the integration of the Spacehab Universal Communications System GPS experiments in the Space Shuttle and spacecraft such as AMSAT and SAC-A. Mr. Davis has also been the lead GPS Simulator test engineer for numerous sounding rocket missions and other spacecraft missions, such as EO-1 and SSTI-Lewis.

Semion Kizhner is an aerospace engineer with the National Aeronautics and Space Administration at the Goddard Space Flight Center. He participated in the development of the Space Shuttle Hitchhiker carrier and payloads such as the Robot Operated Materials Processing System (ROMPS). He was responsible for establishing the GPS applications test facility at Goddard and supported GPS simulations for a dozen space projects, such as the OrbView-2 and SAC-A spacecraft and SIGI project. He graduated from Johns Hopkins University with an MS degree in computer science.

Dr. George W. Davis received his Ph.D. in Aerospace Engineering from the University of Texas in 1996. His research focused on GPS-based precise orbit determination for low altitude geodetic satellites. Currently a Senior Principal Engineer with the Orbital Sciences Corp. in Greenbelt, MD, Dr. Davis works at the NASA Goddard Space Flight Center on spaceborne GPS technology projects, including real-time orbit and attitude determination, formation flying, and GPS space receiver testing.

Requirement Name	Original Amount of Test Hours	Final Amount of Test Hours
Attitude & Navigation Performance	32	112
Cold Start[1]	2.5	12
Warm Start[1]	2.5	12
Maximum Velocity & Attitude Rate[2]	11.25	14.25
Master Antenna Switching[2]	7.5	15
Almanac Upload & Download[2]	7.5	15
Health Message[2]	7.5	7.5
Satellite Selection (Manual & Auto.)[2]	7.5	7.5

1 Each test run was 30 minutes in length and a total of 5 runs.
2 Each test run was 30 minutes in length and a total of 15 runs.

Table 1: A summary of the SIGI receiver requirements tested with initial and final number of test hours.

is canted 41.5° away from the zenith direction[4]. This greatly impacts the ability of the receiver to track enough GPS Satellite Vehicles (SV's) to produce navigation and attitude solutions. Since construction of the ISS will be completed on-orbit, a self survey will not be possible. Therefore, this receiver utilizes a double difference attitude determination algorithm which eliminates the need to precalibrate the receiver using self-survey methods.

The ISS program had 20 different GPS only requirements that had to be verified by engineers at the GSFC GPS Test Facility. These requirements included not only performance specifications for navigation and attitude performance but also several functional requirements. These functional requirements are summarized in the first column of Table 1.

MINIMUM NUMBER OF RUNS

The first question every manager asks a test engineer is how long will it take to prove that a receiver is ready for delivery to the customer. The answer to this question varies greatly depending who is answering and how much experience the customer has had with flying GPS receivers. The first impression that our test team had of the number of runs for assessing navigation and attitude performance was somewhere between six and ten hours for each test run. Four or five test runs was believed to be sufficient, especially if each run was completely different from the other 4 runs (different almanacs and start times). It was also believed that other tests of only 45 minutes would be sufficient to test specific requirements such as: time to first position fix (TTFF), time to first attitude solution (TTFA), performance over an end of week rollover, performance at an altitude above the normal ISS altitude of 300 nautical miles. The complete list of requirements, the originally estimated amount of time for testing that requirement and the final amount of time for testing that requirement is found in Table 1.

The reader will discover that initially estimated number of test hours to adequately characterize the performance of this new receiver was considerably less than the final total of hours. This was a lesson that was learned by many hours of restarting simulations, tracking down small errors in the simulation configuration, or small errors in the operation of the receiver. Some errors were due to problems with the receiver but the majority of problems, during the tests, were due to incorrect simulation and receiver configuration settings that would produce the undesireable results. Trying to determine where the particular problem was in the test setup was the major reason for some many test runs. With so many new parameters being tested at the same time, it was difficult to isolate the true source of the problem. In the future, a Force-19 receiver running in parallel with other new receivers to provide a benchmark on the behavior of the simulator and the new receiver will be a benefit.

Prior to the start of testing, a methodical attempt at determining the minimum number of test runs was performed using statistical sampling techniques. The first issue was the number of simultaneously changing parameters during test runs designed to just look at position, velocity, and attitude performance. If a spacecraft with a GPS receiver is orbiting at an altitude of 250 nautical miles and a constellation of GPS SV's are orbiting at above 9500 nautical miles in different orbit planes, the ability to isolate many of the variables so that one or only a few parameters are changing at a time is very difficult. In honesty, the most practical solution to this aspect of solving for minimum number of runs was to run several very long runs (the more, the better). However, there were many other requirements which could be tested by looking for a sample set of mean values.

The minimum numbers of tests needed to test requirements containing conditions for an event within a mean amount of time or with a certain success rate was calculated. In terms of determining the sample size for the ISS requirements, two types of tests remain: tests with a mean parameter, tests with a success rate parameter.

SAMPLE SIZE OF A MEAN

The first test type deals with a requirement that has a time varying component. For example the calculation for the number of samples to prove a requirement such as Time to First Fix (TTFF), three pieces of information are needed. First the confidence interval is chosen, which in this case is 95%. This confidence interval is then expressed in $Z_{\alpha/2}$ coefficient for a Normal Distribution. This $Z_{\alpha/2}$ coefficient can be found in the back of most Statistics books. Next an initial guess of the standard deviation of the time required

Max. Error of Est.	$Z_{\alpha/2}$ in %	$Z_{\alpha/2}$	Std. Dev.	Sample Size n
1	99%	2.575	10	663
1	95%	1.96	10	384
1	90%	1.645	10	271
5	99%	2.575	10	27
5	**95%**	**1.96**	**10**	**15**
5	90%	1.645	10	11
10	99%	2.575	10	7
10	95%	1.96	10	4
10	90%	1.645	10	3
30	99%	2.575	10	1
30	95%	1.96	10	0
30	90%	1.645	10	0

Table 2: A listing of sample run sizes for a given confidence interval $Z_{\alpha/2}$

the receiver's best performance possible given better than actual conditions. The sinusoidal error was an increase in position error over time because the millisecond value on the clock bias was not used to correct the timetag for the position solution. This slowly growing error was not noticeable until roughly six hours into the run.

Another example of why long test runs are needed occurred when the customer (Johnson Space Center) performed a 24 test run. At 17 hours into the run, the receiver stopped producing attitude, navigation, dropped all tracked GPS SV's and then reset itself. The details of why this problem occurred and the solution to the problem is discussed in more detail in the next section.

A RECEIVER PROBLEM SEVENTEEN HOURS INTO A RUN

A good example of how testing the Force-19 receiver for long periods of time can uncover a very specific and yet critical condition was during a 24 hour test run. At 17:10 into this test run, the GPS receiver began to lose signal lock on all GPS SV's, lost attitude and navigation state knowledge and then performed a power cycle to reset its internal memory. This simulator test was first built by the customer, originally executed by the customer, and once the problem occurred, brought to our attention. The initial reaction was, of course, to blame something other the GPS SG or the GSFC portion of the internal firmware. The next step was to recreate the problem with the test run starting at just a few minutes prior to 17:10 into the run rather retesting the receiver for a full 17 hours. Fortunately this was done and the receiver did reproduce the exact same conditions for the short run as was witnessed during the 17 hour test run. The most immediate navigation parameter which was obviously out-of-spec was that the PDOP value increased from an average of 4 to over 1700 in just 60 seconds. This was the first clue that the problem might lie

Max. Error of Est.	$Z_{\alpha/2}$ in %	$Z_{\alpha/2}$	Std. Dev.	Sample Size n
0.01	99%	2.575	0.99	656
0.01	95%	1.96	0.99	380
0.01	90%	1.645	0.99	268
0.02	99%	2.575	0.99	164
0.02	95%	1.96	0.99	95
0.02	90%	1.645	0.99	67
0.03	99%	2.575	0.99	73
0.03	95%	1.96	0.99	42
0.03	90%	1.645	0.99	30
0.04	99%	2.575	0.99	41
0.04	95%	1.96	0.99	24
0.04	90%	1.645	0.99	17
0.05	99%	2.575	0.99	26
0.05	**95%**	**1.96**	**0.99**	**15**
0.05	90%	1.645	0.99	11

Table 3: A listing of sample run sizes when testing for a success rate (pass or fail) and a confidence interval ($Z_{\alpha/2}$)

in the environment being presented to the receiver. However, no concrete evidence of that fact was available. Therefore the receiver internal software was recompiled to run in a "debug" mode where low-level status information about the firmware would be more available than is usually provided to the users. This did provide some clues as to the possible reasons for the power cycle of the receiver. Some suggestions were made for software changes to both the navigation and attitude firmware to survive an unplanned power cycle during the mission. At the same time, a deeper look at the environment the receiver was presented by the GPS SG was made by test engineers. Upon closer inspection of the settings of the receiver and the GPS SG, it was noticed that the GPS receiver was commanded to look for GPS SV's down to an elevation mask of 0° while the GPS SG was commanded to simulate the constellation to an elevation mask of 5°. At that time, there were only 5 GPS SV's that the receiver had decided it would look for in the GPS constellation. However, the first four all had elevation angles greater than 60° while the fifth and non-simulated GPS SV was at 2.3°. Therefore the receiver used the four high elevation GPS SV's and produced a PDOP solution that was above 1700. By changing the test simulation to simulate GPS SV's that are visible down to 0°, the receiver used the fifth GPS SV and the anomaly never existed for that run.

This particular test scenario was not a very proud moment in the life of the project but it did uncover several important aspects of testing. First, this was the first test in which the receiver was tested for more than 15 hours. It was accidental that this test condition produced this problem. Without the long test, there was a good chance this power cycle condition might never have been found. Sec-

An example of the usefulness of several parameters plotted next to each other on the same page can be found in Figure 4 near the end of this paper.

PACKETVIEW

Test engineers at GSFC were able to capture several parameters at the same time thru the use of a custom program, PacketView, written by Dr. Charles Campbell. Through the use of an initialization file, the user can specify commands that are to be sent either at the beginning of the test run, repeatedly sent at a given rate, or sent once at a certain time into the run. Commands can be sent at any time during the run. Data from the receiver can be captured in binary or ASCII form. For testing of the SIGI receiver, all commands and output from the receiver were saved to a binary file. Certain parameters were routinely analyzed shortly after the run (i.e. position, velocity, time, attitude, PDOP, C/No). These certain parameters were simultaneously captured into an ASCII text file. The captured ASCII data was sorted into individual data files and then imported into post processing tools.

The ability of PacketView data to be broadcast to other servers on our network was very beneficial during very long test runs. During a 12 and 24 hour test run, a quick look at the status of the receiver provided us a way to reduce the amount of wasted test time. This equates to a more immediate respond to a problem without having to actively monitor the receiver at all times during these long test runs. For example, during an overnight run, it was very easy to connect to a secure server at work from a remote location and monitor the status of the receiver. This greatly reduced the cost of having test engineers monitoring the receiver for three work shifts per day. PacketView also has a method of allowing only authorized users to send commands through the use of a password.

TEST RESULTS

The performance of the Force-19 receiver is a success. The receiver provides the navigation and attitude performance required for the ISS. While only using three GPS antennas the receiver has demonstrated near requirement navigation and attitude performance. The most noticeable degradation, while only using 3 antennas, was the loss of satellite coverage. The coverage during the three antenna runs tended to be 10 to 15% less than the coverage for the four antenna test runs.

The receiver has been shown to provide the needed features required for the ISS. For example, the receiver can use a set of antennas which are not zenith pointing. The receiver can accept GPS almanacs and aiding ephemeris for performing a warm start. During a warm start, the average time to a first position solution and then a first attitude solution was 7:49 and 14:35, respectively. On average, during a cold start, the receiver produced it's first position and attitude solutions within 22:58 and 29:39, respectively. The warm start averages were based on 15 different almanac test cases using only 3 antennas while the cold start averages were based on 10 test runs of 5 different almanacs in a three antenna configuration. The cold start tests were considered to be much harder than the warm starts and thus did not require a full fifteen samples to met the desired confidence interval. It was successfully demonstrated that the user can decide which of the four available GPS antennas will be the master antenna for attitude determination. Over the last 14 months, several hundred uploads of GPS almanacs were successful and over 20 different almanacs were collected and downloaded from the receiver to be used in future warm start simulator test runs. It was also successfully demonstrated that the Force-19 can be commanded to drop or attempt intentional track of a user defined GPS SV. The Force-19 also successfully passed end-of-week rollover, August 21, 1999 rollover, and Y2K tests. It was also shown under a test environment that the Force-19 would not attempt to track an unhealthy GPS SV based on almanac data. The receiver demonstrated that it could operate up to the 600 nautical mile altitude limit with three antennas (this is well above any possible ISS altitude). Parameters such as raw pseudorange, carrier phase measurements, GPS ephemeris, and almanac were shown to be made available to a user for future implementation of GPS relative navigation operations with the ISS. The receiver demonstrated that it could acquire and maintain position and attitude during and at a velocity of 12 $\frac{km}{sec}$. However, the receiver could only maintain attitude at 5 $\frac{deg}{sec}$ while the requirement was for 20 $\frac{deg}{sec}$.

A snapshot of the navigation and attitude performance from the Force-19 receiver under ISS configurations during a GPS Signal Generator test run can be found in Figures 4 and 5.

In Figure 4 all error values are one sigma numbers in meters and the data are shown only when the current PDOP value is $\leq$ than six. Also included in Figure 4 are the values of PDOP under six and then PDOP values for all instances of a position solution. Next the number of tracked GPS SV's (according to the Force-19 receiver) are plotted versus time. This is followed by the receiver's value of Carrier to Noise ratio (C/No). Finally, the signal strength (as presented by the GPSSG) is plotted. It should be noted that the receiver can only measure C/No (a measure of how clean the signal is in the receiver). The coverage value listed at the top of the figure was computed while screening the position solutions for PDOP $\leq$ to six. Horizontal lines at PDOP value of six, at 35 dB Hz for C/No plot, and -95 dBm and -65 dBm bound the range of acceptable values as listed in the ISS requirements document[3].

In Figure 5, the attitude determination performance (attitude error) of the receiver is shown for each axis and a RSS of the attitude error is shown along the bottom plot in this figure. This plot also lists the attitude coverage. This attitude coverage is not screened for ADOP values of less than 0.06 $\frac{deg}{mm}$ (which is a screening criteria used in the ISS GN&C flight software). Along the top of each plot is the mean error value, standard deviation value, Root Mean

Square of the error, 3 σ value of the error (provided the data exhibits a Gaussian distribution), and the number of data points listed in the particular plot.

The navigation performance, in the Position Error RSS plot of Figure 4, shows that the Force-19 is adequate with some caveats. For example, near the start of the test run, the Force-19 has a large position error spike. This spike occurred even when the PDOP solution was $\leq$ to six. This error spike occurred again about halfway through the test run. Notice that in the PDOP $\leq$ six plot, that at that time a large amount of change has occurred with respect to the number of GPS SV's which were tracked. This was not even a reflection on the amount of switching the GPS SV's within the channels in the receiver and how that might affect navigation solution performance. Another note of interest should be the fact that the values of PDOP and number of tracked PRN's did not have a timetag. Several approaches were taken in order to try and synchronize the PDOP and number of tracked PRN data with the position error data. During certain portions of the run, the GPS receiver was too busy in order to service the telemetry and provide data to the user. This means that missing gaps of data can not be correlated to a timetag. This is a source of error that will have to be discussed with the customer and a course of action will then be decided upon. At this time, it is the conclusion of the test team that the lack of timetag may be one of the sources of the large position error spikes. Other possible sources of error are being investigated.

Within Figure 4, the C/No and Truth Signal Strength plot demonstrates that the receiver can track signals at a reasonably weak signal level. Given the amplification of the preamplifiers used in the test setup, the GPS Signal Generator was tuned to provide the signal levels that were within the range of -95 dBm to -65dBm. These boundary values are represented as the solid horizontal lines in the Truth Signal Strength plot. The goal of the testing was to demonstrate that the receiver could track GPS signal at the C/No levelof atleast 35 dB-Hz. This is easily seen in the plot C/No where the data points reach and sometimes fall below the 35 dB-Hz threshold (shown as a solid horizontal line in the plot).

The attitude performance plots, Figure 5, illustrate the attitude errors from the time the Force-19 was powered on until the time the power was turned off. The Force-19 took 5 minutes and 56 seconds to calculate its first attitude solution. It should be noted that this was a four antenna test configuration with very little multipath injected into the simulator. The noticeable features of these plots were the greatest attitude error appeared along the Pitch axis and the attitude error spikes sometimes appeared on all three axes and sometimes only one axis. The fact that the worst axis for attitude performance was along the roll axis was not a coincidence. In fact, this axis lies along the short side of the retangular GPS antenna array. This shortest distance of the rectangle leads to a decrease in attitude accuracy. The second noticeable point from these plots was not so obviously explained. Attitude error spikes only occurring along one axis was typical behavior for Force-19 attitude performance. However, the ISS GN&C flight software will screen the attitude solutions using a long-term averaged value of an ADOP matrix to be $\leq 0.06 \frac{deg}{mm}$ [5]. These types of errors are usually taken out at the expense of attitude coverage. It should also be noted that the errors do not contain a bias which makes the data suitable for use in the on-board ISS GN&C flight software attitude Kalman Filter.

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References

[1] Kaplan, Elliott D. (ed.), Understanding GPS: Principles and Applications, Boston: Artech House Publishing, 1996.

[2] Hogg, Robert, and Tanis, Eliot, Probability and Statistical Inference, Upper Saddle River, NJ: Prentice Hall, 1997.

[3] Honeywell Inc., Appendix 90 Prime Item Development Specification for the International Space Station Integrated GPS/INS Navigation System (SIGI-ISS), Sensor and Guidance Products, Clearwater, Florida, November 6 1998, DS34204000.

[4] United States. National Aeronautics and Space Administration. Integrated Truss Segment S0 to Global Positioning System Interface Control Document Publication SSP 50103. Houston, TX: Johnson Space Center, 1999.

[5] United States. National Aeronautics and Space Administration. Project Technical Requirements Specification for the International Space Station (ISS) Global Positioning System (GPS) Subsystem. Publication JSC26656. Houston, TX: Johnson Space Center, 1995.

[6] United States. National Aeronautics and Space Administration. The International Space Station: An Overview. Publication SIS-1999-06-ISS022. Houston, TX: Johnson Space Center, 1999.